93-01449/

Bull. Soc. géol. France, 1991, t. 162, n° 2, pp. 283-298

CONTRIBUTION
SERIES

91-002

Peat formation in a Westphalian B piedmont setting, Cumberland basin, Nova Scotia : implications for the maceral-based interpretation of rheotrophic and raised paleomires

by JOHN H. CALDER*, MARTIN R. GIBLING** and PRASANTA K. MUKHOPADHYAY***

Key words. – Peat, Peat-forming environments, Paleomires typing, Maceral analysis, Westphalian B, Cumberland basin, Canada, Nova Scotia.

Abstract. – A maceral-based method of interpretation of ancient peat-forming ecosystems (mires) is proposed, based on criteria used in classification of modern peatlands (groundwater influence, nutrient and ionic supply, pH and vegetation type). This method relies heavily upon an index of groundwater influence (GWI), supported by a vegetation [illegible] (VI). The degree of biochemical gelification of plant tissues and the abundance of mineral matter were used as variables in the calculation of [illegible] caution is advised in the use of inertinite as an indicator of paleomire type. VI contrasts lignin-derived forest products against macerals of [illegible]eous and aquatic affinity; paleobotanical verification is recommended for fuller reconstruction of floral community. The No. 3 seam of the rapidly subsiding Westphalian B Cumberland Basin, Nova Scotia, was chosen as a case study. Profiles were studied from each of the piedmont, inner mire and riverine zones of the seam. The inner mire zone is marked by overall upward decreasing trends of gelocollinite, ash and sulphur contents and an upward increasing trend of telinite and telocollinite which reflect temporal change to more acidic and less groundwater influenced conditions. The piedmont zone profile is petrographically similar to the base of the inner mire profile. The inner mire evolved through terrestrialization from swamp through swamp forest to fen and questionably, to bog/bog forest, recording evolution from rheotrophic to mesotrophic or ombrotrophic conditions. The piedmont margin, subject to periodic, fan-derived sheetflood, developed through a cogenic mechanism of paludification, whereas the evolution of the mire at the riverine margin experienced allogenic influences (e.g. differential compaction). Although the mire may have ultimately achieved an ombrotrophic status, the seam developed primarily as a rheotrophic (and mesotrophic) ecosystem.

Formation de tourbe dans un environnement de piedmont du Westphalien B, bassin de Cumberland, Nouvelle Ecosse : implications pour l'interprétation macérale des paléotourbières rhéotrophiques et surélevées

Mots clés. – Tourbe, Environnements de dépôt, Typologie des tourbières, Analyse macérale, Westphalien B, Bassin de Cumberland, Canada, Nouvelle Ecosse.

Résumé. – L'article propose une méthode d'interprétation des paléotourbières, fondée sur l'analyse macérale, et s'appuyant sur les critères utilisés dans la classification des tourbières modernes (niveau d'eau, apports en éléments nutritifs, pH et type de végétation). Cette méthode prend notamment en compte l'index d'influence du niveau d'eau (GWI) et l'index de végétation (VI). Le degré de gélification biochimique des tissus de plantes et l'abondance de la matière minérale ont été utilisés comme variables dans le calcul du GWI; on souligne la précaution qu'il convient de prendre dans l'utilisation de l'inertinite en tant qu'indicateur de type de tourbière. L'index de végétation exprime le rapport entre les composants issus de plantes ligneuses (forêt) et les composants issus de plantes herbacées ou aquatiques; il est recommandé d'effectuer des vérifications paléobotaniques pour reconstruire de manière plus complète l'assemblage floristique. La couche n° 3 du Westphalien B du bassin Cumberland, en subsidence rapide, a été choisie comme étude de cas. Des profils ont été étudiés dans chacuns des domaines de la couche, piedmont, tourbière interne et tourbière de rivage. La tourbière interne est marquée par des teneurs en gélocollinite, en cendres et en soufre, décroissantes vers l'amont, et par des teneurs en télinite et télocollinite croissantes vers l'amont, ce qui traduit le passage à des conditions plus acides et moins influencées par le niveau d'eau. La zone de piedmont est pétrographiquement similaire à la base du profil de la tourbière interne. La tourbière interne a évolué dans le sens d'une terrestrialisation, depuis un marais vers une forêt marécageuse, enregistrant ainsi l'évolution des conditions rhéotrophiques aux conditions mésotrophiques ou ombrotrophiques. La marge de piedmont, soumise à des dépôts d'inondation périodiques, s'est développée par un mécanisme de paludification, alors que l'évolution du marécage de la marge littorale a subi des influences allochtones (avec compaction différentielle). Bien que la tourbière ait pu atteindre des conditions ombrotrophiques en phase finale, la couche s'est surtout déposée dans un écosystème rhéotrophique (et mésotrophique).

I. – INTRODUCTION

In a classic paleoecological study of Westphalian coals of Britain, A.H.V. Smith [1962] drew an analogy to the peatlands of tropical Malaysia and Indonesia, which were first recognized by Polack [1933] as being raised (ombrogenous) rather than topogeneous. By the early 1980s, raised peatlands were invoked by sedimentologists to explain some aspects of the architecture of Tertiary coal-bearing fluvial successions [Flores, 1981; Ethridge *et al.*, 1981]. Since then, raised peatlands have been invoked to account for numerous features of both coals and fluvial architecture [Esterle and Ferm, 1986; Warwick and Stanton, 1988, Warwick and Flores, 1987]. The raised peatland has become a favored concept of ancient mire development, dominating the papers at the 1987 Egham Conference [see Teichmüller,

* Coal Section, Nova Scotia Department of Mines and Energy, P.O. Box 1087, Halifax, Nova Scotia, Canada B3J 2X1.
** Department of Geology, Dalhousie University, Halifax, Nova Scotia, Canada B3H 3J5.
*** Global GeoEnergy Research Ltd., P.O. Box 9469, Station A, Halifax, Nova Scotia, Canada B3K 5S3.
Note présentée au Colloque d'Orléans du 12 au 15 septembre 1989, déposée le 18 octobre 1989; manuscrit définitif accepté le 14 mai 1990.

TABLE I. – Wetland ecosystems and hydrological types of mires. [Based upon Moore, 1987].
TABLE I. – *Écosystèmes des domaines marécageux et types de tourbière (selon le caractère hydrologique).*

CRITERION:	WETLAND ECOSYSTEMS			
Peat Accumulation:	PEAT - FORMING (MIRES)			NON PEAT-FORMING
Water Source:	RAIN-FED (OMBROTROPHIC)	FLOW-FED (RHEOTROPHIC)		
Water Level:		Dry Season Water Table		
		Below Surface	Above Surface	Near Surface
Ecosystem:	Bog	Fen [1]	Swamp [2]	Marsh [3]
Vegetational varieties:	(bog forest)		(floating swamp, swamp forest)	

[1] sensu stricto as orginally proposed by Tansley (1939). Moore and Bellamy (1974) and Gore (1983) applied fen in the broader sense to all rheotrophic mires.

[2] "swamp" in the United States commonly refers to forested wetlands (Penfound, 1952) without regard to accumulation of peat. Those swamp forests which are peat-forming are similar to Scandinavian "carr".

[3] As orginally proposed by Tansley (1911). In United States, marsh and swamp are commonly differentiated by presence (swamp) or absence (marsh) of trees (Penfound, 1952).

1989, pp. 60-66 for a comprehensive discussion]. Indeed, Moore [1987] concluded that "the modern successors to the 'coal swamps' are clearly not swamps at all but are bog forests of an ombrotrophic nature" (see table I). He emphasized that for low ash and sulphur coal, "such material can only have developed in an ecosystem of a tropical "forest' type in which the abundant supply of water was entirely by precipitation, i.e. ombrogenous".

Although the Recent bog forests of Indonesia and Malaysia clearly have potential to form low ash coal, it seems unlikely that all coals formed entirely as raised peatlands. Teichmüller [1982] considered that most bituminous coal seams were deposited in eutrophic swamps into which abundant nutrients for the peat-forming vegetation were brought through regular flooding by rivers, lakes or the sea; the ash yields and the many clay and marl intercalations in the coal seams provided evidence of flooding. These two conflicting views of ancient peatland development serve as the backdrop for the hypothesis to be investigated in this paper. Teichmüller [1989, p. 66] noted that the recognition of coals that have been deposited under oligotrophic and ombrogenous conditions remains one of the most intriguing problems to be solved.

Earlier methods of paleoenvironmental analysis based on coal petrography of Paleozoic coals include those of Teichmüller and Teichmüller [1958], Hacquebard and Donaldson [1969] and Diessel [1982, 1986]. The authors not only concur with the opinion expressed by Collinson and Scott [1987] that simple models based solely on coal petrography may lead to erroneous paleoenvironmental interpretations, but suggest that few such studies have used parameters similar to those employed in modern mire classification. The following considerations therefore apply : (i) maceral-based analysis should be supported through disciplines such as paleobotany and geochemistry; (ii) the method used should be based on parameters similar to those employed in the classification of modern mires. The purpose of this paper is to identify these parameters and the role of coal macerals in their determination.

The Number 3 seam of the Springhill coalfield, in the Cumberland basin of Nova Scotia, is considered here in the context of an ancient peat-forming ecosystem. Concepts of paleoenvironmental interpretation developed in this study draw heavily upon the comprehensive treatise on peat-forming ecosystems edited by Gore [1983]. Palynomorph data are incorporated in the paleoecological interpretation of this ancient mire deposit in a separate publication (Calder, in press).

II. – GEOLOGICAL SETTING OF THE SPRINGHILL COALFIELD

The Springhill coalfield is located adjacent to the Cobequid highlands massif near the southern margin of the Cumberland basin (fig. 1), a component of the larger Maritimes basin of eastern Canada. The Maritimes basin formed within a transcurrent zone between the compressional orogenic regions of the Appalachians and Urals [Arthaud and Matte, 1977] and was deformed along its southern margin

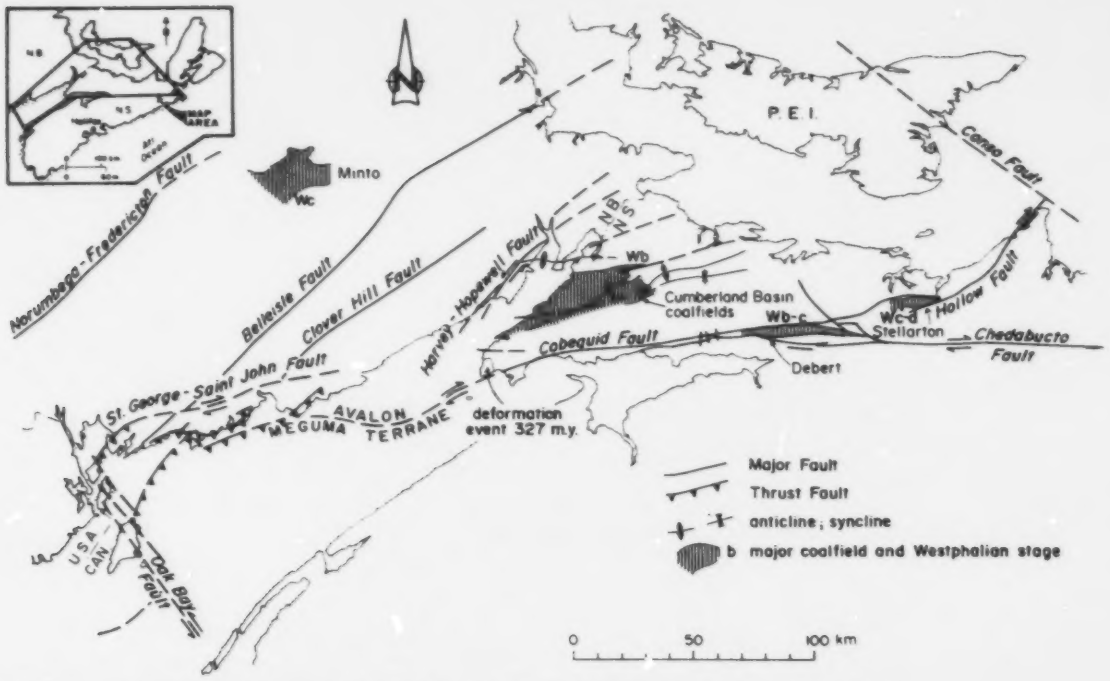


FIG. 1. – Location and tectonic setting of Westphalian coalfields of the southern Maritimes basin, eastern Canada.

FIG 1. – *Localisation et cadre tectonique des bassins houillers westphaliens, dans la partie sud du bassin Maritimes dans l'est du Canada.*

during the late Carboniferous (Silesian) by dextral strike-slip along major faults [Eisbacher, 1969; Keppie, 1982; Donohoe and Wallace, 1985; Nance, 1987].

During the Westphalian B, the Cumberland basin was the major depocenter within the southern Maritimes basin, when 4 km of basin-fill represented by the Cumberland Group was deposited during a 3 million year [Lippolt and Hess, 1985] period. The basin occupied a tropical, near-equatorial paleolatitude [Scotese *et al.*, 1979]. A seasonally drier paleoclimate has been envisaged for the Euramerican coal province during the Westphalian B [Phillips *et al.*, 1985] but an ever-wet tropical climate was inferred for the Appalachian basin [Cecil *et al.*, 1985]. The local paleoclimate of the Maritimes basin and the effect (e.g. rainshadow) of the rising Appalachian mountains have yet to be determined.

III. – COAL-BEARING STRATA OF THE SPRINGHILL COALFIELD

Coal-bearing strata of the Springhill coalfield comprise > 840 m of a 4 km-thick basinal fill (fig. 2) of the Cumberland Group [Bell, 1944], which includes the Polly Brook, Joggins, and Springhill Mines formations. This basin-fill is of predominantly Westphalian B [Hacquebard and Donaldson, 1964] and probably also late Westphalian A age [Bell, 1944] and forms an overall fining and ultimately reddening-upward lithologic sequence.

During deposition of the major coal-bearing lithofacies assemblage of the Springhill Mines Formation within which the No. 3 seam occurs, peat-forming wetlands from 4 to 7 km wide flourished at the toe of a piedmont of coalesced alluvial fans derived from the Cobequid highlands massif to the south. The wetlands were bordered to the north by a basin-axis river belt 1-2 km wide. As a result of the interaction of the peat-forming ecosystems and neighbouring geomorphic regions, the thickest and most areally extensive seams of the Springhill coalfield exhibit three areal zones defined by the lithology and geometry of the seams and siliciclastic splits, best exemplified by the No. 3 seam (fig. 3) : (i) a southern, **piedmont zone;** (ii) an **inner zone;** and (ii) a northern, **riverine zone.**

The coals of Springhill are high volatile bituminous but increase in rank at depth to medium volatile [Hacquebard and Donaldson, 1970]. In the profiles studied herein, the No. 3 seam exhibits an R_o max of 0.87 to 0.99. The No. 3 seam attains a maximum thickness (devoid of partings in the inner mire zone, drillhole SH81) of 4.32 m and extends 6.5 km from north to south (fig. 3). The seam is presumed to have developed along the basin margin, however its original east-west extent is unknown due to post-depositional erosion to the east and to the great depth of the coal-bearing strata to the west, beyond the extent of drill and mine data. Within the inner mire zone (SH81), the volumetrically weighted ash (as received basis) and sulphur contents of the seam are 10.1 and 1.7 percent, respectively. Ash content

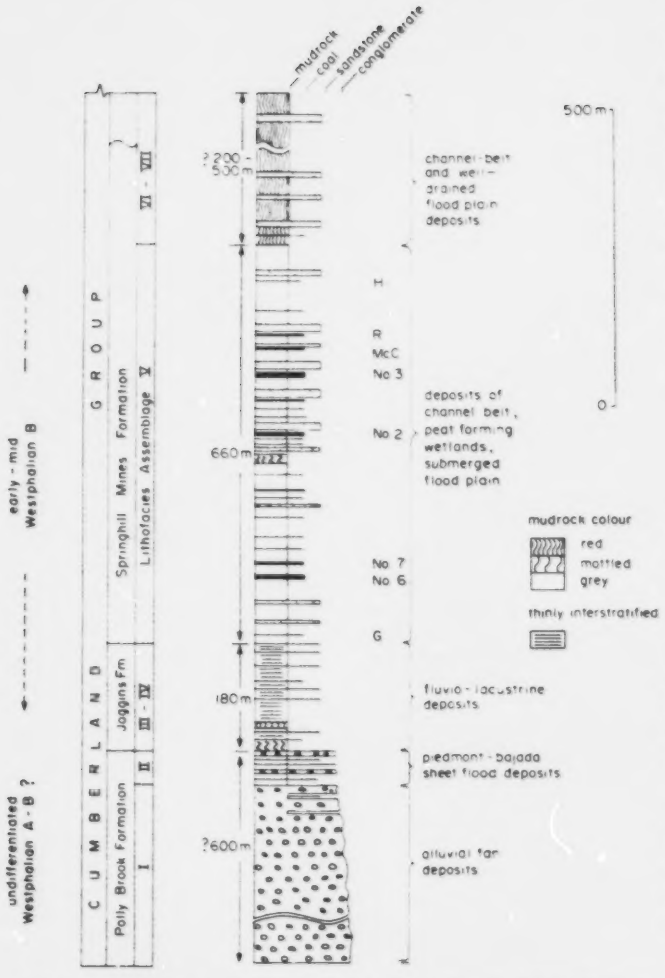


FIG. 2. – Basin-fill sequence of the Cumberland Group, Springhill coalfield.

FIG. 2. – *Sequence stratigraphique du Groupe Cumberland, bassin houiller de Springhill.*

rises progressively both toward the basin margin and axis, whereas sulphur increases to > 3 % at the basin margin and to > 5 % toward the basin axis; this increase is due primarily to variation in the content of pyritic sulphur (0.9 to 5.6 %) rather than sulphate (nil to 0.27 %) or organic (0.7 to 0.8 %) forms.

IV. – CLASSIFICATION OF MODERN PEATLANDS

In this study, the recommended classification of Moore [1987] is followed (table I) in which wetland ecosystems are subdivided into freshwater peatlands (**mires**) and non peat-forming wetlands. The most fundamental distinction of mire types is based on hydrology, specifically the source of water and ions. **Rheotrophic** mires receive recharge from both groundwater and rainfall, whereas **ombrotrophic** mires are solely rain-fed. (The term **minerotrophic,** which refers to a mineral-rich groundwater source, is loosely analogous to rheotrophic). An intermediate classification of **mesotrophic** applies to mires tending toward ombrotrophic conditions. Ombrotrophic mires are termed **bogs**; rheotrophic mires can be subdivided into **fen** or **swamp** depending on the range of flooding with respect to the mire surface, whereas **marshes** do not accumulate peat *per se*. Varieties of bog, fen and swamp are further defined on the basis of vegetation (e.g. bog forest, swamp forest). Mires additionally can be classified as eutrophic (nutrient rich) or oligotrophic (nutrient poor). The reader is referred to Gore [1983], Moore [1987, 1989] and Kosters *et al.* [1987] for further discussion of wetland nomenclature.

V. – ATTRIBUTES OF MIRE DEVELOPMENT

The principal attributes cited in characterization of modern mires are : (1) groundwater influence [Kulczynski, 1949; Moore and Bellamy, 1974; Gore, 1983; Etherington, 1983]; (2) nutrient/ionic supply [Kulczynski, 1949; Gore, 1983; Moore, 1987]; (3) ash content [Gore, 1983; Moore, 1987] and (4) vegetation type [Gore, 1983; Moore, 1987]. The first three of these are functions of the two primary variables in the development of peat-forming plant communities : water supply and ionic supply [Kulczynski, 1949, Tallis, 1983]. Water supply (mean water table level and fluctuation of this level) in turn controls ionic supply. Ions can be supplied, in order of increasing contribution, from (i) meteoric input (precipitation); (ii) immobile ground water; and (iii) mobile ground water [Tallis, 1983]. Hence, rainfed, ombrotrophic mires have restricted ionic replenishment, whereas strongly rheotrophic mires fed by flowing water have the greatest supply of ions, tending to be rich in nutrients and relatively high in pH and ash content [Gore, 1983; Moore, 1987]. Two examples of modern rheotrophic wetlands and mires which have a moderate to high pH value are the Everglades of southern Florida and the *Cyperus papyrus* swamps of Uganda and Sudan in East Africa. The Everglades, which overlies a Pleistocene limestone, has calcium-rich soil and neutral to alkaline peat with a maximum pH of 8.6 [Teichmüller, 1982]. The rheotrophic papyrus swamps of East Africa typically exhibit a pH of 6-6.5 [Beadle, 1974]. The pH is thought to be controlled chiefly by the volume of dissolved CO_2 in the swamp waters; a decrease in CO_2 concentration occurs with flooding, thereby increasing pH levels [Beadle, 1974].

Such an abundance of nutrients and a moderate to high pH level, amplified by oxygenated waters and by the presence of the alkaline ions, promotes early humification and biochemical gelification [Teichmüller, 1982, 1989]; bacteria may assist in this process [Teichmüller, 1982]. The result is an increase in strongly humified and gelified plant matter, hence unstructured forms of huminite/vitrinite. Development of a mire from rheotrophic to mesotrophic or ombrotrophic conditions therefore will be manifested within a coal bed by, amongst other things, (1) decrease in ash content; (2) increase in structured forms of vitrinite; and (3) evidence of floral succession (fig. 4).

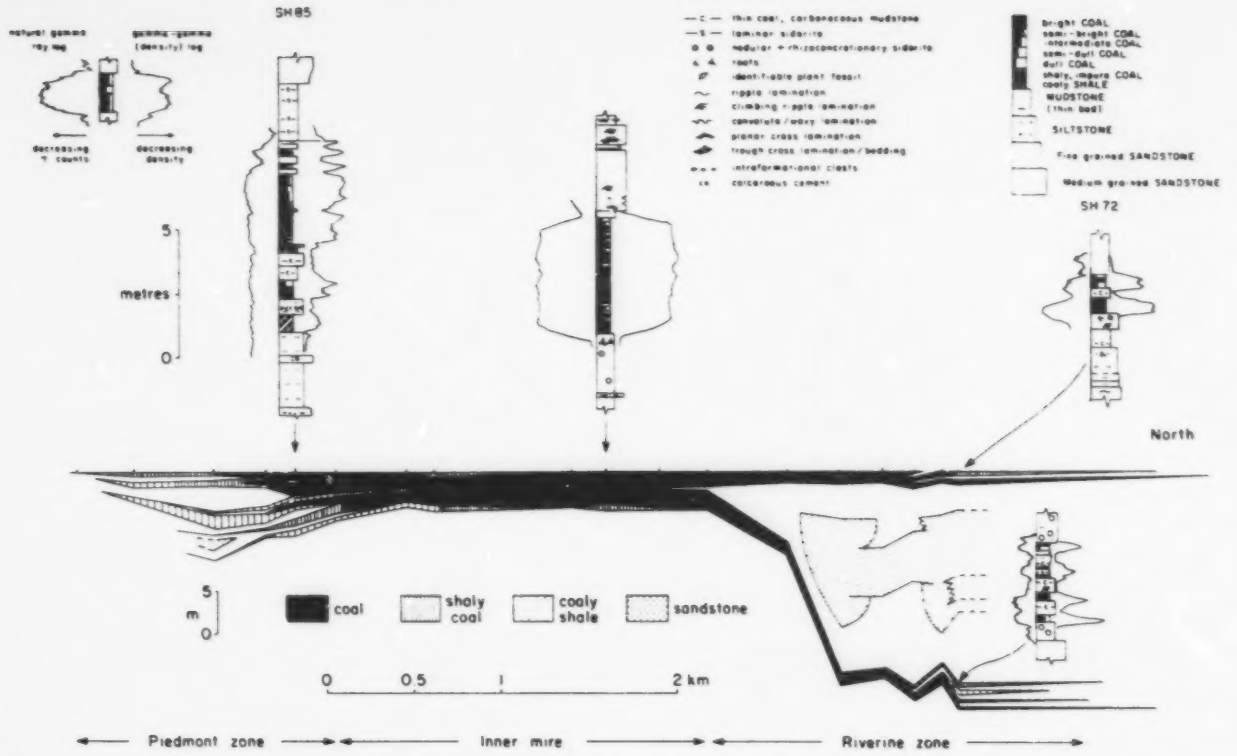


FIG. 3. – Transverse (N-S) cross-section of the No. 3 seam, Springhill coalfield, showing profiles of drill-core subjected to maceral analyses discussed in this study.

FIG. 3. – *Coupe transversale du filon houiller No. 3, bassin houiller de Springhill, montrant les profils des carottes de forage soumises à l'analyse des macéraux et décrits dans cette étude.*

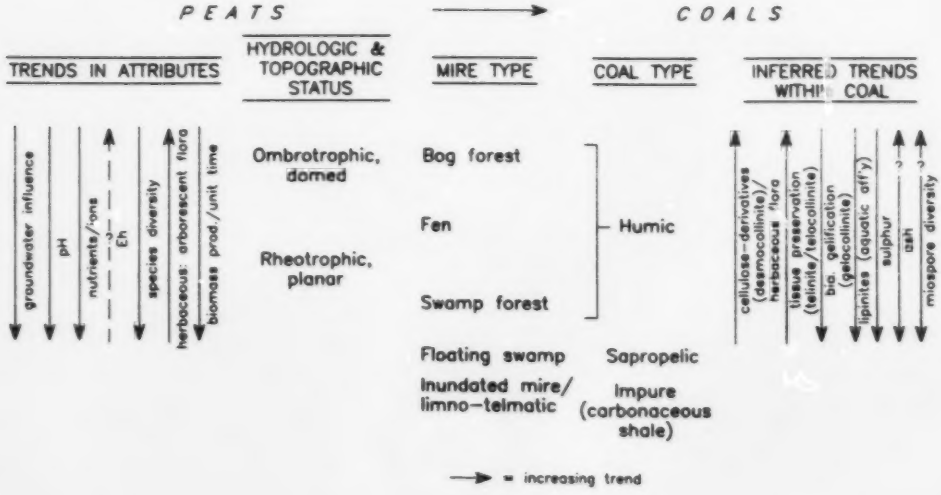


FIG. 4. – Genezalized trends of attributes within principal rheotrophic to ombrotrophic peat-forming mire types, and of attributes inferred for corresponding coal types.

FIG. 4. – *Tendances d'ensemble des caractères des principaux types de tourbière rhéotrophiques à ombrotrophiques à tourbe et des caractères des types de charbon correspondants.*

Changes in the environmental variables of water movement and ionic supply arise chiefly from modification to hydrology or topography [Tallis, 1983]; such change may be **autogenic** (self-induced) or **allogenic** (externally induced). Certain mires evolve through self-induced modification to the mire hydrology from rheotrophic to ombrotrophic. Such autogenic evolution is recorded in the peat stratigraphy [Moore, 1987]. The sequence of mire types which results from such change is referred to as an **hydroseral** succession. The mechanism by which mires evolve in this manner, termed **terrestrialization,** has long been recognized within temperate mires of the northern hemisphere [verlandung of Weber, 1908].

Although Moore [1987] stated that such successions are unknown for tropical forested mires, evidence for a basic hydrologic evolution has been documented. The tropical forest bogs of Indonesia and Malaysia are reportedly ombrotrophic [Anderson, 1964]. These mires originate, however, as rheotrophic forest swamps [Polak, 1975] and have evolved from a minerotrophic to oligotrophic status [Cameron *et al.*, 1989]. In reference to the concentric zonation of plant communities in Southeast Asia mires and the palynology from one such peat deposit, Anderson [1983, p. 195] found clear evidence that the ombrotrophic peat developed over [rheotrophic] mangrove soils, and the catenary sequence of forest types represents a succession in time.

In this study, a maceral-based method of recognizing various types of paleomire ecosystems was developed using similar criteria to those recommended for modern mire classification by Gore [1983] and Moore [1987]. Since "it is both convenient and ecologically meaningful... to classify mires on the basis of hydrology, or more specifically, on their main source of ionic input" [Moore, 1987, p. 11] the fundamental distinction between rheotrophic and ombrotrophic paleomires must first be considered. Further subdivision of these two main hydrologic types can be achieved by assessing the vegetation of the mire, either indirectly through maceral analyses or directly from paleobotanical studies.

VI. – Maceral ratios in paleomire analysis

The fundamental concept employed in this study is that the classification and study of modern peat-forming systems provides a basis for interpretation of coal (fossil peat) deposition. This concept stems from the work of Teichmüller and Teichmüller [1958] and of Teichmüller [1962], Hacquebard and Donaldson [1969] and Diessel [1986]. Historically, macerals have been less favoured than microlithotypes in paleoenvironmental studies of coal [Teichmüller, 1962; Hacquebard *et al.*, 1967 : Bustin *et al.*, 1985]. In recent years, however, the use of maceral analysis in paleoecological studies [Diessel, 1982, 1986; Mukhopadhyay, 1986, 1989; Stanton *et al.*, 1987] has developed largely in response to the overwhelming availability of this form of analysis [Diessel, 1986] and has been made possible by the refinement of maceral determination, particularly within the vitrinite group, and increased knowledge of the genesis of such macerals [Stout and Spackman, 1987; Mukhopadhyay, 1991; Teichmüller, 1989]. Development in fluorescence microscopy and studies of macerals in the lignite and peat stages have contributed to this refinement.

Various methods have been used for the paleoenvironmental interpretation of maceral analyses, from the ratio of vitrinite : inertinite employed by Harvey and Dillon [1985] to the more involved maceral ratios of Diessel [1982, 1986]. The development of techniques to assess specific parameters of the ancient peat mires is a daunting task, given the endless permutations of maceral ratios possible. Four factors which must be taken into account in such a study are : (1) the botanical precursor of the macerals [Teichmüller, 1982; 1989, her Table I]; (2) diagenetic pathways of the macerals and their precursors [Teichmüller, 1982; 1989; Mukhopadhyay, 1991]; (3) transport of plant matter from its site of origin to site of accumulation within the paleomire [Diessel, 1986, and this study]; and (4) the secondary nature of some macerals (e.g. exsudatinite; micrinite) formed during subsequent coalification [Teichmüller, 1989, her Table I].

A) Groundwater index

The ratio of strongly gelified (gelocollinite, desmocollinite, corpocollinite) to weakly gelified tissues (telinite, telocollinite) should provide a relative measure of gelification and by inference, of water supply and pH. Gelocollinite, however, is the product of biochemical gelification of predominantly lignin-derived humins [Techmüller, 1982], whereas desmocollinite is derived at least in part from cellulose-rich herbaceous vegetation [Teichmüller, 1989]. Cellulose showed an upward increase in abundance within a modern tropical forest peat from Sarawak [Esterle *et al.*, 1989] and, although cellulose within the upper peat layers will be reduced by degradation [cf. Casagrande *et al.*, 1985], the inferred trends for relatively strongly gelified tissues in desmocollinite and gelocollinite may oppose each other because they reflect, among other things, differences in original plant matter. The change to herbaceous vegetation arises due to hydrological modification of the mire surface and is therefore a measure of groundwater influence, albeit an indirect one. Trends in vegetation type therefore are to a large degree a function of groundwater influence and groundwater and vegetation indices will be very much inter-related. The intensity of rheotrophic conditions can be evaluated using the following ratio, referred to as the **groundwater influence index (GWI) :**

$$\frac{\text{gelocollinite} + \text{corpocollinite} + \text{mineral matter}}{\text{telinite} + \text{telocollinite} + \text{desmocollinite}}$$

The utilization of the GWI as given requires the subdivision of the vitrinite maceral collinite into telocollinite, gelocollinite, desmocollinite and corpocollinite. Vitrinite is classified in earlier literature as vitrinite A or B, with a third type C corresponding to pseudovitrinite [Brown *et al.*, 1964]. However, according to ICCP nomenclature, vitrinite A corresponds to telocollinite whereas vitrinite B corresponds to desmocollinite [Stach, 1982]; vitrinite A and B do not incorporate gelocollinite and corpocollinite. In a gelocollinite-rich coal such as the No. 3 seam, the exclusion of these two maceral types would render the GWI totally inaccurate. Even if vitrinite A and B were redefined to cor-

respond to structured and unstructured forms, the system is not suitable for use in recognizing the evolution of trophic status in an ancient mire (coal). Desmocollinite and gelocollinite reflect, in part, cellulose vs lignin-rich material [Teichmüller, 1989] and may therefore record opposing trends in some seams (see fig. 4). Corpocollinite additionally may occur as isolated bodies within structured telocollinite.

A test of GWI calculated using the ratio given above and recalculated on the basis of internally structured (telinite, telocollinite) versus all unstructured vitrinite (gelocollinite, desmocollinite and corpocollinite) + mineral matter led to a slight increase in GWI, with the integrity of the plots (see below) remaining essentially unchanged, but only because desmocollinite occurs in low abundance (see fig. 4). The genetically based system employed by the Institute of Geology of the Academy of Sciences of USSR [Timofeev and Bogoliubova, 1964; ICCP Handbook, 1971] however, is potentially useful in that vitrinite is described as having a telinitic, posttelinitic, precollinitic, collinitic or leiptinitic (*sic*) structure; such a sequence reflects increasing gelification and decomposition and could be incorporated readily in an index of groundwater influence.

Photomicrographs of the five vitrinite macerals and maceral types recognized in this study (telinite, telocollinite, gelocollinite, desmocollinite, corpocollinite) are shown in plate I and criteria for their recognition, based on ICCP definitions, are given in the appendix to this paper.

The use of mineral matter in the groundwater influence index rests on the assumption that it is largely of detrital origin, although mineral matter appears to be used as a criterion for classification of modern mires and peats regardless of its origin. A mire subject to flooding is by definition rheotrophic. Some mineral matter will be diagenetically and biochemically derived [Cecil *et al.*, 1979], but should comprise a relatively small proportion of the total. Dramatic increases in mineral matter (locally up to 77 volume % in the No. 3 seam) within a specific zone or seam section, particularly when associated with siliciclastic partings whose geometry and sedimentology suggest a fluvial origin, are most probably indicators of increased groundwater influence. Kaolinitic tonstein beds of volcanic origin should be omitted in the calculation of groundwater influence, but none have been identified to date from seams of the Springhill coalfield.

B) Vegetation index

Theoretically, mires can be broadly subdivided on the basis of vegetation type by contrasting macerals of forest affinity with those of herbaceous and marginal aquatic affinity. More accurate paleoecological reconstruction necessitates incorporation of paleobotanical study. Lignin-rich vegetation of a forest habitat is represented by telocollinite, fusinite and semifusinite; suberinite and resinite are associated macerals. Although gelocollinite and corpocollinite are assumed to be derived largely from lignin and tannins, respectively, their origin is less clear than the origin of telinite and telocollinite, for instance, hence their exclusion in this version of a vegetation index. Paleomire plots for the inner mire region utilizing a vegetation index (see below) excluding gelocollinite and corpocollinite are compared in figures 9a and 9b, respectively. Herbaceous, cellulose-rich vegetation is represented in part by desmocollinite, inertodetrinite and liptodetrinite [Teichmüller, 1989; Mukhopadhyay, 1989]. Truly aquatic conditions are indicated by alginite, representing planktonic algae. No higher plants (macrophytes) from the late Carboniferous have thus far been identified as truly aquatic [Collinson and Scott, 1987], and thus the term "marginal aquatic" is invoked to represent the truly aquatic algae plus those macerals which preferentially accumulated in the limno-telmatic zone, irrespective of their site of origin (e.g. sporinite). Sporinite and cutinite are included in this study because of their similar distribution to other marginal aquatic macerals within the No. 3 seam. The resulting measure of vegetation type, referred to as the **vegetation index (VI)**, can be expressed as :

$$\frac{\text{telinite + telocollinite + fusinite + semifusinite + suberinite + resinite}}{\text{desmocollinite + inertodetrinite + alginite + liptodetrinite + sporinite + cutinite}}$$

The vegetation ratio is similar to the "tissue preservation index" (TPI) of Diessel [1986], which was given as :

$$\frac{\text{telinite + telocollinite+ semifusinite+ fusinite}}{\text{desmocollinite + macrinite + inertodetrinite}}$$

The main departure in this study from Diessel's TPI is the inclusion of vegetation and plant matter of aquatic affinity. Diessel [1982] considered gelocollinite to be an insignificant contributor to Australian Permian coals, although he later [Diessel, 1986] chose to include macrinite, a fusinitized gel [Teichmüller, 1982], in his TPI. A similar maceral ratio was developed by Mukhopadhyay [1989] for Texas Tertiary coals to characterize various wetland settings (swamp, swamp-marsh, marsh, aquatic).

C) Mire paleoenvironment diagram

The genesis of the ancestral, late Carboniferous paleomire of the No. 3 seam, Springhill coalfield, can be modelled in part through maceral data by plotting the index of relative groundwater influence (GWI) against the vegetation index (VI) (fig. 5). This method of evaluating paleomire type to a large degree continues the development of methods introduced by Diessel [1986], but differs from previous methods (e.g. Diessel [1986] in which TPI was plotted against GI) primarily in the utilization and definition of a measure of groundwater influence, which as stated earlier, is the fundamental criterion for mire classification [Moore, 1987].

The major mire types identified (fig. 5), i.e. limnic (essentially open water) areas, swamp, fen and bog, represent a succession from rheotrophic to ombrotrophic hydrological conditions and eutrophic to oligotrophic nutrient status (cf. fig. 4). Above a groundwater influence index of approximately 3, the ecosystem is considered to be predominantly limno-telmatic (at or below the water table). High GWI values, in excess of 5, represent a wetland paleoenvironment prone to siliciclastic inundation, where impure coal lithotypes formed (shaly coal, coaly shale and carbonaceous mudstone). The terms inundated "marsh" (*sensu lato*) and inundated forest (*sensu stricto*) are used here, whereas the terminology for modern peat-forming systems seems inadequate for the description of such marginally peat-forming paleoenvironments. The term marsh is warranted due to the

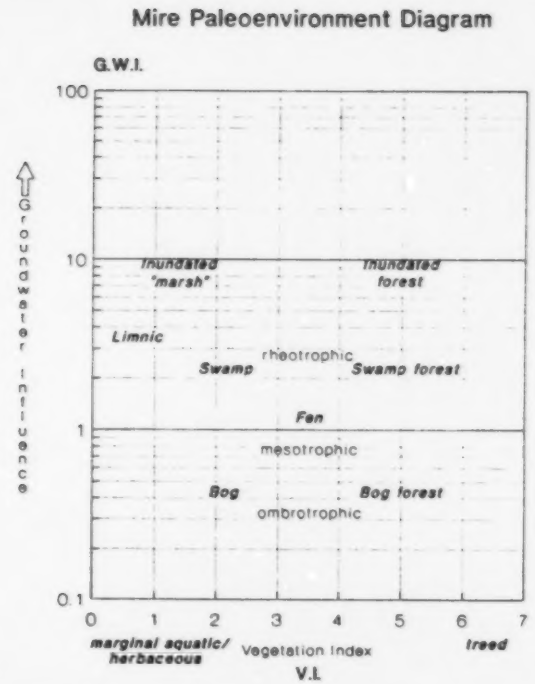


FIG. 5. – The mire paleoenvironment diagram.

FIG. 5. – *Diagramme des paléoenvironnements de tourbières.*

interpreted marginal aquatic/herbaceous nature of the wetland vegetation [Penfound, 1952] and due to the high ash content of organic sediments in such a setting which strictly falls outside the classification of a peat-forming ecosystem [Moore, 1987; see also table I).

A GWI value of 0.5 is proposed arbitrarily as the level below which groundwater ceased to be influential and the mire became solely rain-fed. The choice of this value is discussed below with respect to the No. 3 seam.

The participation of forest vegetation in the ecosystem is represented by the x-axis; a vegetation ratio of 3 or greater is considered to represent a predominantly forested mire. It should be possible, therefore, to recognize a swamp forest within the swamp mire type, or a bog forest within the bog type. Much emphasis has been given in past studies to a relative measure of Eh. For example, Harvey and Dillon [1985] used the vitrinite : intertinite ratio exclusively; Diessel [1986] utilized a similar ratio of :

$$\frac{\text{vitrinite} + \text{macrinite}}{\text{semifusinite} + \text{fusinite} + \text{inertodetrinite}}$$

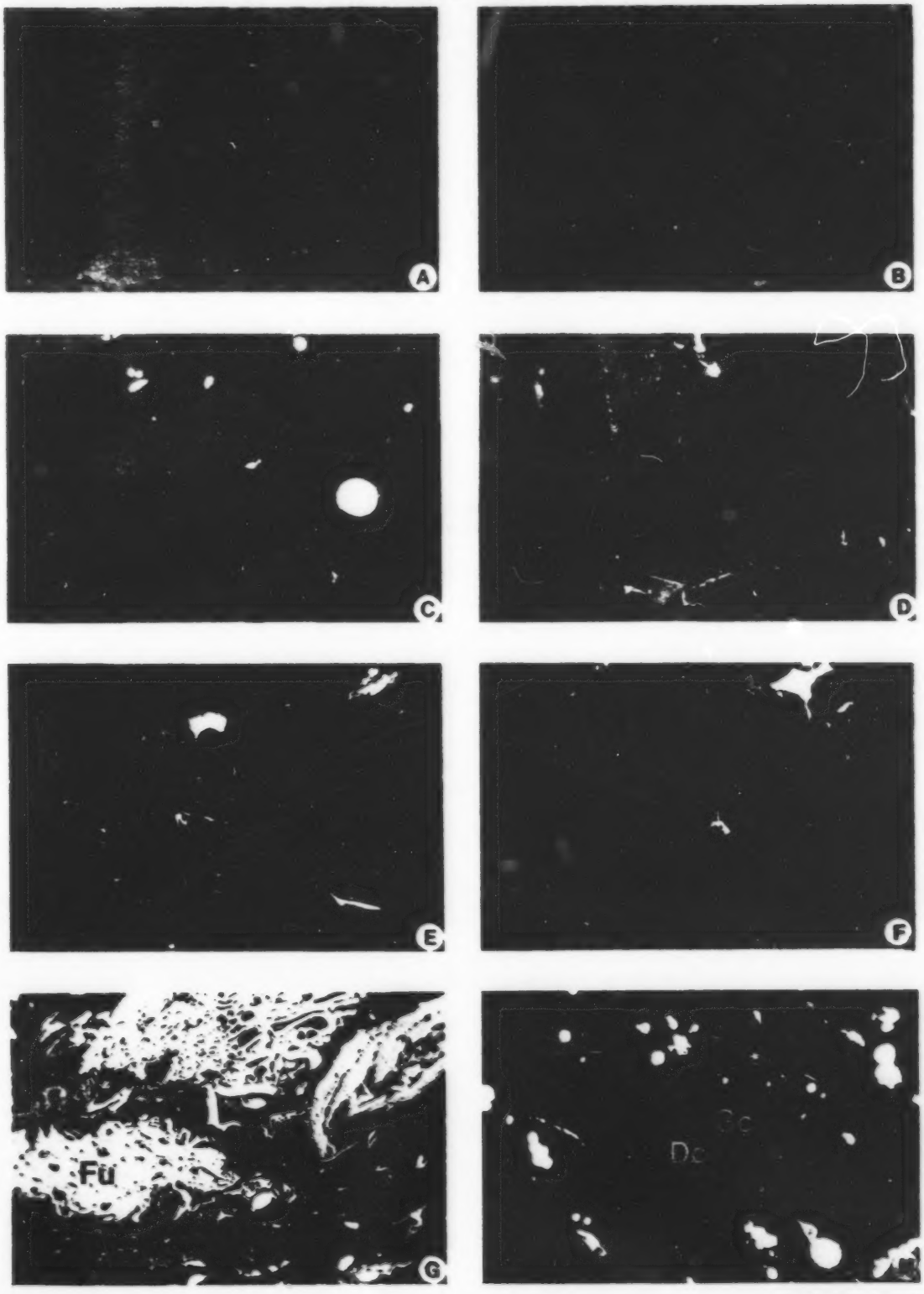
which he termed a gelification index (GI; although as given it more accurately reflects the oxidation of tissues); and Mukhopadhyay [1989] classified a mire as oxic to anoxic primarily on the basis of inertinite. Although the writers recognize the potential usefulness of certain inertinite macerals in paleomire analysis and the great emphasis historically placed upon inertinite as a paleoenvironmental indicator, the decision not to utilize it as an independent variable in the present study was based on three key points : (1) in the literature on modern peat-forming ecosystems [e.g. Gore, 1983; Moore, 1987], Eh was rarely if ever mentioned as a definitive criterion; (2) the maceral fusinite within Carboniferous coals (and particularly within the No. 3 seam) is often [Teichmüller, 1982] of the variety pyrofusinite (plate I) and although certain low reflecting inertinites may form through other processes [Teichmüller, 1989] no direct evidence for a non-fire (microbial) origin of fusinite has to date been demonstrated from modern peat mires [Cohen and Spackman, 1977; Cope and Chaloner, 1985]. Scott [1989] concluded that the macroscopic lithotype fusain originated as charcoal, probably of wildfire origin. Fires within the mire are events, more closely associated with prolonged periods of low rainfall [cf. Anderson, 1983, p. 182, but see Scott, 1989] than with specific ecological zones within the mire complex [Cope and Chaloner, 1985; Collinson and Scott, 1987, p. 75]; indeed such fire can raze even water-logged environments [Scott, 1989]; (3) fusinite, in particular, commonly has been found in this study [see also Guerra-Sommer *et al.*, this volume] to be allochthonous, occurring in seam section rich in ash and alginite (plate Ig). Although the mire vegetation elsewhere may have been experiencing oxic conditions, the site of accumulation need not have. Similar reservations on the usefulness of using semifusinite and fusinite as indicators of dry conditions were expressed by Mastalerz and Smyth [1988, p. 325].

VII. – THE NO. 3 SEAM : MACERAL ABUNDANCE PROFILES

Maceral analyses (volume percent) were conducted manually on 52 particulate grain mounts of the No. 3 seam (raw coal) under both incident white light and blue-light excitation using 1000 point counts. Sample intervals (see seam profiles, figs. 6-8) corrrespond to single macroscopic lithotypes or similar associations of lithotypes and comprised whole core. The complete seam profile was sampled; siliciclastic partings greater than 0.10 m were excluded

PLATE I. – Photomicrographs from the No. 3 seam, Springhill coalfield and coal 14, MacCarron Creek, Cumberland Basin in reflected light (× 500 magnification) : A : telinite (81-1T); B : telocollinite (81-1T); C : gelocollinite (Gc) and telocollinite (Tc) (MC 14); D : corpocollinite (Cc), desmocollinite and micrinite 81-7T); E : desmocollinite and sporinite (81-1T); F : desmocollinite and telocollinite (81-7T); G : fusinite (Fu), mineral matter, bituminite and liptodetrinite (81-13T); H : gelocollinite (Gc), desmocollinite (Dc), cutinite, sporinite, micrinite and pyrite framboids (Mc 14).

PLANCHE I. – *Macéraux du filon houiller N° 3, bassin houiller de Springhill, et du filon 14, Rivière MacCarron, Bassin Cumberland, lumière réfléchie (× 500) :* A : *télinite (81-1T);* B : *télocollinite (81-1T);* C : *gélocollinite* (Gc) *et télocollinite* (Tc) *(MC14);* D : *corpocollinite* (Cc), *desmocollinite et micrinite (81-7T);* E : *desmocollinite et sporinite (81-1T);* F : *desmocollinite et télocollinite (81-7T);* G : *fusinite* (Fu), *matière minérale, bituminite et liptodetrinite (81-13T);* H : *gélocollinite* (Gc), *desmocollinite* (Dc), *cutinite, sporinite, micrinite et pyrite (MC14).*


A
B
C
D
E
F
Fu
G
Sc
Dc

from petrographic analysis). Proximate analysis and sulphur determination (weight percent) were conducted using ASTM procedures. One representative diamond-drill core was chosen from each of the three areal zones of the seam, primarily on the basis of core recovery, after matching detailed macroscopic (lithotype) profiles with 1 : 25 scale gamma and density signatures.

Maceral analyses for the piedmont, inner mire and riverine zones of the No. 3 seam, presented graphically in figures 6, 7 and 8, respectively, revealed several key points : (1) predominance of the vitrinite maceral group in all three zones; (2) predominance of unstructured vitrinite (predominantly gelocollinite; plate 1c) over structured vitrinite (telinite/telocollinite; plate 1a,b) in all areas except

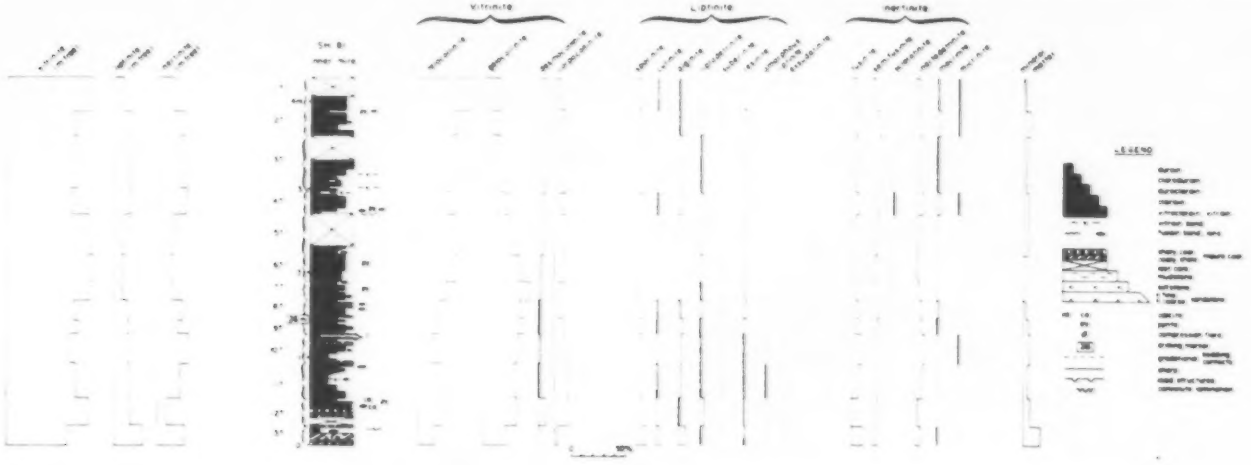


FIG. 6. – Maceral abundance profile, inner mire zone (SH 81).

FIG. 6. – *Profil de l'abondance des macéraux, zone intérieure de la tourbière (SH 81).*

FIG. 7. – Maceral abundance profile, piedmont zone (SH 85).

FIG. 7. – *Profil de l'abondance des macéraux, zone de piémont (SH 85).*

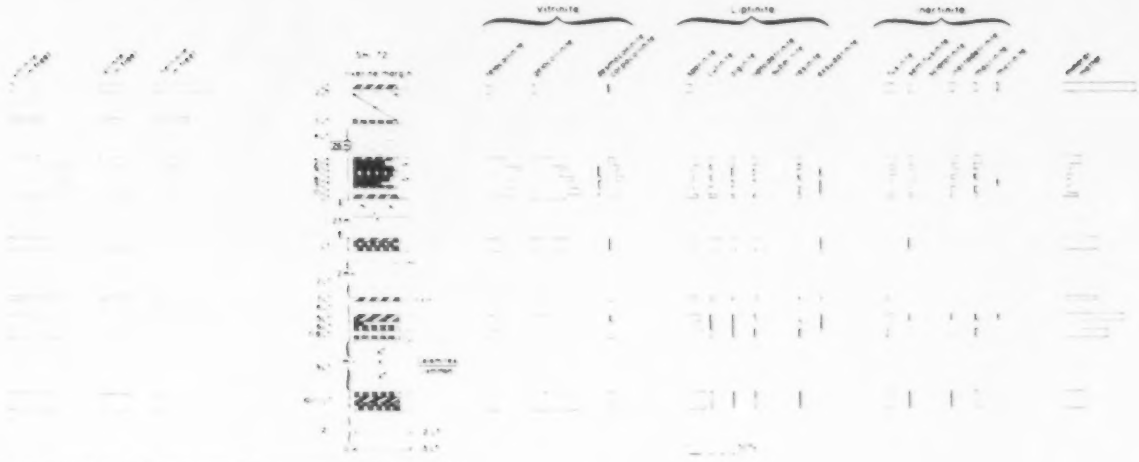


FIG. 8. – *Maceral abundance profile, riverine zone (SH 72).*
FIG. 8. – *Profil de l'abondance des macéraux, zone fluviale (SH 72).*

the upper half of the seam in the inner mire; (3) high content of liptinite (especially sporinite and, locally, alginite) at the seam base (plate 1g); (4) petrographically distinct areal zones; (5) distinct vertical zonation based on maceral and ash content in the inner mire section (fig. 6); and (6) contrasting petrographic composition between upper and lower seam leaves in the riverine zone (fig. 8).

VIII. – THE NO. 3 SEAM : RECONSTRUCTION OF PALEOMIRE TYPES

Figure 9a is a paleomire plot of the No. 3 seam from the inner mire. Samples 13 to 8 from the basal 1.76 m of the seam (SH 81) cluster about the designation of swamp, transitional to fen. The upper 2.56 m of the seam (samples 7-1) show progressively lower GWI and variable VI values. The seam thus shows a partial hydroseral succession of mire types, from swamp through swamp forest and fen, perhaps culminating in weakly developed bog and ultimately bog forest. Mineral matter decreases upward (from 16.4 to 2.0 volume percent), as does gelocollinite, suggesting a temporal evolution in mire chemistry to more acidic conditions. Telinite plus telocollinite, increasing upward at the expense of gelocollinite, reaches a maximum of 42.4 percent at the seam top. Upward-decreasing ash and sulphur contents (fig. 5), ground water influence index (GWI) and pH within the inner mire suggest an evolution from minerotrophic toward oligotrophic conditions. Although formed in a different geomorphic setting, the inner zone of the No. 3 seam is in this respect similar to the bog forest of the Baram River district of Sarawak as described by Cameron *et al.* [1989, their fig. 12].

An inferred increase in rheotrophic conditions from samples 6 to 5, near mid-seam, is represented by the dashed line in figure 9a : examination of the seam profile and corresponding downhole geophysical logs reveals that some impure coal and possibly carbonaceous mudstone within sample 4 was not recovered during coring. Correlation of this thin parting with the 22 m-thick parting to the north (fig. 3) indicates that this reversal in the overall hydroseral succession occurred while the northern periphery of the mire, the riverine zone, was drowned; a fluvial channel-belt subsequently occupied this margin. The overall autogenic evolution of the mire ecosystem was thus temporarily interrupted by this allogenic "event".

With abandonment of the fluvial tract in the neighbouring riverine zone, the inner mire experienced mesotrophic evolution from a fen (samples 4-3) under much decreased influence of groundwater. As groundwater influence continued to dininish from sample 3 to 2, the mire is interpreted to have evolved to a predominantly (mesotrophic), if not wholly (ombrotrophic), rain-fed ecosystem. Maceral data suggest that the climax mire (sample 1) was probably bog forest, but other data suggest deflation of the mire surface [Calder, in press]. This uppermost sample has a GWI value of 0.37, the ratio of telocollinite + desmocollinite to gelocollinite is 3.8:1 and mineral matter content is a mere 2.0 volume percent. The conditions under which these values would simultaneously occur are clearly ones of negligible groundwater influence, but whether they reflect mesotrophic or truly ombrotrophic conditions is difficult to ascertain. Although this a crucial point in determining whether ombrotrophic mires were precursors of presently mineable coal seams, it may not be possible to unequivocally differentiate between mesotrophic and ombrotrophic conditions. In terms of nutrient supply, the seam exhibits an evolution from eutrophic (minerotrophic) to oligotrophic conditions.

The piedmont zone (SH85; fig. 9c) records at best a weakly developed hydroseral succession of mire types from limnic and swamp to fen, as expected in an area characterized by a readily available water supply [Grosse-Brauckmann, 1979; Teichmüller, 1989]. The seam is characterized by strongly rheotrophic conditions and inundation

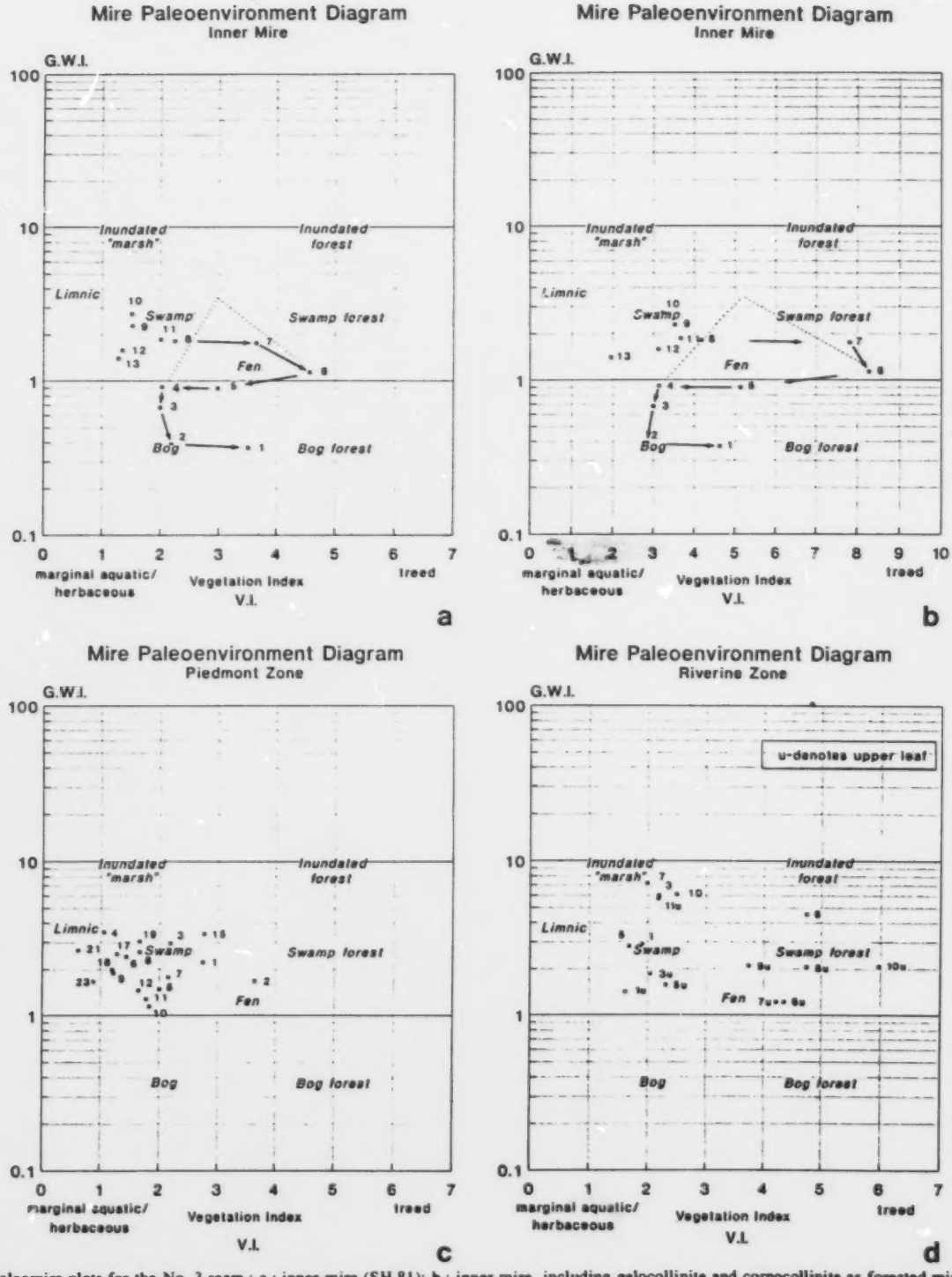


FIG. 9. – Paleomire plots for the No. 3 seam : a : inner mire (SH 81); b : inner mire, including gelocollinite and corpocollinite as forested mire indicators in the numerator of the VI; c : piedmont zone (SH 85); d : riverine zone (SH 72).

FIG. 9. – *Diagrammes d'environnement des paléotourbières pour le filon houiller n° 3 : a : zone intérieure (SH 81); b : zone intérieure où la gélocollinite et la corpocollinite sont utilisées pour indiquer l'influence forestière au numérateur de l'index de la végétation (VI); c : zone de piémont (SH 85); d : zone fluviale (SH 72).*

throughout the 6.2 m thick section; the groundwater influence index remains above 1.38.

The riverine zone, (drillhole SH72; fig. 9d) records highly rheotrophic conditions, with the GWI ranging from 1.21 to 5.94. There was a marked difference in both mire vegetation and groundwater influence between the lower and upper leaves of the No. 3 seam which in the riverine zone are separated by a multistorey sandstone body. The lower leaf accumulated in inundated aquatic (limno-telmatic "marsh") and forest environments dominated by inferred marginal aquatic and herbaceous vegetation, evolving only slightly to swamp. The partial drowning of the northern margin of the mire and the later avulsion to this site by a major fluvial system are doubtless related. Following northward relocation of the channel belt, the mire was re-established as inundated "marsh" (sample 11UT) in the riverine zone (upper leaf). Forest vegetation spread from the inner mire which survived this interval of fluvial occupation. The northern margin remained rheotrophic but became significantly less prone to inundation, evolving to swamp and fen environments.

Waters affecting the piedmont and riverine margins and basal inner-mire zone of the seam had potential to contribute alkaline ions to the mire although the source of ions would have varied. The piedmont margin was inundated periodically by sheetflows traversing alluvial fans, whereas the riverine margin was inundated periodically by flood waters of the basin-axis river system. Possible sources of alkaline ions which would have contributed to the gelification of tissues within the mire include : (1) basin-margin springs associated with faults underlying the Springhill coalfield; and (2) eroding marine limestones of the Windsor Group (Visean spores are reported from siliciclastic partings at the northern riverine margin : Dolby [1988]). Although marine waters could have supplied alkaline ions to the peat, there is no known record of marine influence in the Springhill Mines Formation.

IX. – Processes of paleomire development

The process by which the mire evolved is analogous to terrestrialization [verlandung : Weber, 1908] in recent temperate mires and to "vertical paludification" described for the tropical bog forests of the Baram River area, Sarawak by Cameron *et al.* [1989]. Large-scale (first order) trends in maceral distribution and the overall, upward-brightening trends of lithotypes, within the inner and piedmont zones of the mire reflect autogenic evolution. Although dulling-upward trends in coal have been suggested [Esterle and Ferm, 1986; Littke, 1987; Warwick and Flores, 1987; Eble and Grady, 1989] as an analogue for tropical domed peat mires, an overall upward-brightening trend was considered by Esterle *et al.* [1989] and Cameron *et al.*, [1989] to be the expected signature from the bog forests of tropical Indonesia. The data for the No. 3 seam suggest that successional change occurred throughout the life of the mire rather than recurring in a cyclic manner, a trend predicted by McCabe [1984].

The piedmont zone vegetation developed under strongly rheotrophic conditions. Examination of the macroscopic petrographic/sedimentological cross-section of the seam simplifed in figure 3 indicates that the mire advanced progressively toward the basin margin, which suggests that the ecosystem was able to withstand episodic sheetflow from the piedmont fans. A mechanism applicable to mire development at the piedmont margin has been described for Recent temperate mires by Kulczynski [1949] and Heinselman [1963]. Kulczynski proposed that mires of Pclesie can develop progressively upslope by impeding drainage of land of slightly higher topography; he termed this process "upslope paludification". A similarly self-induced (autogenic) process was described by Heinselman for mires in the Lake Agassiz region of Minnesota.

As described above, the No. 3 seam is characterized in the vicinity of SH85 by the vertically coincident termination of many siliciclastic partings. This suggests that this area of the seam represents a limit of detrital incursion from the piedmont into the mire throughout the development of the seam. It is possible therefore that the piedmont zone was a weakly developed topographic feature of the mire, similar to the sloping margin of the bog forests of Sarawak and Brunei described by Anderson [1964] and analogous to the "rand" of temperate raised bogs [Anderson, 1983; Gore, 1983].

In the riverine zone, both peat formation and channel-belt course were balanced by differential compaction of entombed channel sandstone bodies, peat and floodplain muds; faulting indicated in mine workings also may have exerted an allogenic control at the riverine margin. Waterlogged conditions induced by rapid subsidence of the riverine margin, are evidenced by a high liptinite content and fungal attack, presumably on moribund arborescent lycopods (Calder, in press). Drowning was a harbinger of later fluvial occupation. Relief inherited from an entombed, 12m-thick multistorey sandstone body (fig. 3) resulted in lesser groundwater influence during formation of the upper leaf, permitting the development of swamp and fen types (fig. 9d).

X. – Conclusions

The two main parameters available to coal geologists in the interpretation of paleomire types are : (1) an index of groundwater influence and (2) an index of vegetation. Of these, a measure of groundwater influence is fundamental to the interpretation of rheotrophic versus ombrotrophic paleomires. Genetically based vitrinite maceral determination and mineral matter distribution are two important indicators of groundwater influence. Although the maceral ratio indices chosen for this study will doubtless be modified, particularly as advances continue with respect to the origin of macerals, the parameters of groundwater influence and vegetation remain the major criteria employed in modern peatland classification. Individual researcher's analyses may differ in the degree of interpreted biochemical gelification, but areal and vertical trends in vitrinite preservation should nonetheless reveal trends in the trophic development of a seam. The index of vegetation, used in this study to contrast lignin-rich forest derivatives with other types, may be less well suited to maceral-based studies, for it relies on the macerals being predominantly *in situ*. It may be advisable therefore to contrast a measure of groundwater

influence against floral community as determined, for instance, from palynology to more objectively assess mire paleoecology. (For comparison of results from this maceral-based method and those from miospore analysis, see Calder, in press).

Overall upward-decreasing trends of gelocollinite, ash and sulphur contents and the increasing-upward trends of telinite and telocollinite reflect a temporal change in the mire to more acidic conditions under lessened influence of groundwater, inferred to reflect evolution of the mire from rheotrophic *toward* ombrotrophic conditions.

It is important to realize that the peatlands of tropical Indonesia and Malaysia, while presently raised (ombrotrophic), were earlier rheotrophic ecosystems. Although the ancestral mire of the No. 3 seam may have tended toward an ombrotrophic status in the inner zone, it was essentially a rheotrophic ecosystem. The interaction of peat-forming and neighbouring depositional processes resulted in the development of a mire complex marked by significant lateral and vertical variation in mire type.

Acknowledgements. – The bulk of the research in this paper was funded by the Coal Section, Nova Scotia Department of Mines and Energy. J.H.C. expresses gratitude to his colleagues for their support and encouragement, and for valuable discussion over the course of the study. The paper benefited from critical reviews by P. Bertrand and P.J. McCabe; C.F.K. Diessel provided valuable comments on a related portion of the PhD thesis of J.H.C.. Thanks are due to M. Avery, Atlantic Geoscience Center, for use of his microphotography equipment, and to B. Cassidy for assistance in computer plots. We acknowledge Canmet laboratory and Atlantic Coal Institute for the chemical analysis. Drafting conducted by the Cartography Section, photography by R. Morrison, typing by J. Cumby and B. Hawkins, NSDME, and translation by M.C. Williamson and P. Bertrand are gratefully acknowledged.

Appendix

In coals of bituminous rank, there are three macerals within the vitrinite group : telinite; collinite; and vitrodetrinite. The telinite maceral has two submacerals (telinite 1 and telinite 2), whereas the collinite maceral has four submacerals (telocollinite, gelocollinite, corpocollinite, and desmocollinite). In normal reflected light, all these macerals and submacerals are gray. The reflectance of desmocollinite is lower than that of telinite, telinite is lower than telocollinite, which is lower than gelocollinite. Corpocollinite has the highest reflectance. The following are the characteristics of the five vitrinite macerals and submacerals :

Telinite : This maceral shows nongelified plant tissues with well-preserved cells, often filled with phyllotelinite [Stach *et al.*, 1982] or corpocollinite or resinite or colloresinite (plate 1a). The cell walls are called telinite. In high volatile bituminous rank, this submaceral is nonfluorescent under ultraviolet excitation. Textinite or texto-ulminite is the low rank counterpart of telinite.

Telocollinite : This submaceral shows partially homogenized and gelified cells, when cell walls and cell infillings have similar reflectance or cell lumens are not filled. It is produced from biochemical and geochemical gelification and often shows relict cell structures (plate 1b). Similar to telinite, it is nonfluorescent in ultraviolet excitation. Eu-ulminite or ulminite B is the low rank counterpart of telocollinite.

Gelocollinite : It is a completely homogenized and gelified submaceral showing smooth gray color and contains no relict cell structures (plate 1c, h); nonfluorescent like telinite. It is formed from the colloidal precipitation of humic gel [Stach *et al.*, 1982]. Porigelinite and levigelinite are the low rank counterparts of gelocollinite.

Corpocollinite : Similar to gelocollinite, corpocollinite is also a completely homogenized submaceral. However, it always has a round or oval shape and occurs either as isolated bodies or as cell fillings (plate 1d) and generally originated from humic gel. It is nonfluorescent like gelocollinite. Corpohuminite is the low-rank counterpart of this submaceral.

Desmocollinite : This submaceral shows fine-grained detrital fragments, which are completely homogenized and gelified. This submaceral is possibly derived mainly from humic detritus mixed with minor amount of liptinitic groundmass (plate 1 e, f). In high- and medium-volatile bituminous rank, this submaceral shows brown fluorescence. In reflected light, it is often associated with patches of granular micrinite. Attrinite and densinite are the low-rank counterparts of this submaceral.

Références

ANDERSON J.A.R. (1964). – The structure and development of the peat swamps of Sarawak and Brunei. – *J. Trop. Geogr.*, **18**, 7-16.

ANDERSON J.A.R. (1983). – The tropical swamps of Malesia : *In* : Gore A.J.P. Ed., Mires : swamp, bog, fen and moor (regional studies); ecosystems of the World 4B. – Elsevier, Amsterdam

ARTHAUD F. & MATTE P. (1977). – Late Paleozoic strike-slip faulting in southern Europe and northern Africa : result of a right-lateral shear zone between the Appalachians and the Urals. – *Geol. Soc. Amer. Bull.*, **88**, 1305-1320.

BEADLE L.C. (1974). – The inland waters of tropical Africa : an introduction to tropical limnology. – Longman, London.

BELL W.A. (1944). – Carboniferous rocks and fossil flora of northern Nova Scotia. – *Geol. Surv. Canada, Mem.*, **238**, 277 p.

BROWN H.R., TAYLOR G.H. & COOK A.C. (1964). – Prediction of coke strength from the rank and petrographic composition of Australian coals. – *Fuel*, **43**, 43-54.

BUSTIN R.M., CAMERON A.R., GRIEVE D.A. & KALKREUTH W.D. (1985). – Coal petrology : its principles, methods and application. – *Geol. Assoc. Canada*, Short Course Notes 3, 2nd revised edition, 230 p.

CALDER J.H. (1991). – The evolution of a groundwater-influenced (Westphalian B) peat-forming ecosystem in a piedmont setting : the No. 3 seam, Springhill coalfield, Cumberland Basin, Nova Sco-

tia. – *Geol. Soc. Amer. Spec. Paper*, Modern and ancient environments of coal formation. (in press).

CAMERON C.C., ESTERLE J.S. & PALMER C.A. (1989). – The geology, botany and chemistry of selected peat-forming environments from temperate and tropical latitudes. – *Int. J. Coal Geol.* **12**, 443-475.

CASAGRANDE D., FERGUSON A., BOUDREAU J., PREDNY R. & FOLDEN Ch. (1985). – Organic geochemical investigations in the Okefenokee Swamp, Georgia : the fate of fatty acids, glucosamine, cellulose and lignin. – Compte Rendu Neuvième Congrès International de Stratigraphie et de Géologie du Carbonifère, Madrid, 1983, **4**, 193-204.

CECIL C.B., RENTON J.J., STANTON R.W. & FINKELMAN R.B. (1979). – Mineral matter in coals of the central Appalachian Basin. – Ninth International Congress of Carboniferous Stratigraphy and Geology, Urbana; abstract, p. 33.

CECIL C.B., STANTON R.W., NEUZIL S.G., DULONG F.T., RUPPERT L.F. & PIERCE B.S. (1985). – Paleoclimatic controls on late Paleozoic sedimentation and peat formation in the central Appalachian Basin (U.S.A.). – *Int. J. Coal Geol.*, **5**, 195-230.

COHEN A.D. & SPACKMAN W. (1977). – Phytogenic organic sediments and sedimentary environments in the Everglades – mangrove swamp – marsh complex. Part II. Petrography of peats. – *Palaeontographica* B, **162**, 71-144.

COLLINSON M.E. & SCOTT A.C. (1987). – Implications of vegetational change through the geological record on models for coal-forming environments. *In :* SCOTT A.C. Ed., Coal and coal-bearing strata : recent advances. – *Geol. Soc. Spec. Publ.*, **32**, 67-85.

COPE M.J. & CHALONER W.G. (1985). – Wildfire : an interaction of biological and physical processes. *In :* Tiffney B.H., Ed., Geological factors and the evolution of plants. – Yale University press, New Haven, 257-277.

DIESSEL C.F.K. (1982). – An appraisal of coal facies based on maceral characteristics. *In :* MALLET C.W. Ed., Coal resources. Origin, exploration and utilization in Australia. – Symposium proceedings; Geol. Soc. Australia Inc. Coal Group, 474-483.

DIESSEL C.F.K. (1986). – On the correlation between coal facies and depositional environments. *In :* Advances in the study of the Sydney Basin. – Proceedings of the 20th Newcastle Symposium, 19-22.

DOLBY G.(1984). – Palynological examination of 60 samples from the Springhill coalfield, Nova Scotia. – Unpublished Robertson Research Canada Ltd. report RRC/84/2238, 17 p.

DOLBY G. (1988). – Palynological analysis of the No. 3 and Rodney seams, Springhill and other samples from the Cumberland Basin, Nova Scotia. – Unpublished Nova Scotia Department of Mines and Energy report, 70 p.

DONOHOE H.V.J. & WALLACE P. (1985). – Repeated orogeny, faulting and stratigraphy in the Cobequid Highlands, Avalon terrain of northern Nova Scotia. – Geol. Assoc. Canada/Mineral. Assoc. Canada Joint Annual Meeting, Field Trip Excursion 3, 76 p.

EBLE C.F. & GRADY W.D. (1989). – Comparative palynologic and petrographic characteristics of Middle Pennsylvanian coal beds and a probable modern analog. *In* : Geol. Soc. Amer. 1989 annual meeting, Abstr. Progr. **21**, 6, A26.

EISBACHER G.H. (1969). – Displacement and stress field along part of the Cobequid fault, Nova Scotia. – *Can. J. Earth Sci.*, **6**, 1095-1104.

ESTERLE J. & FERM J.C. (1986). – Relationship between petrographic and chemical properties of coal seam geometry, Hance seam, Breathitt Formation, southeastern Kentucky. – *Int. J. Coal Geol.* **6**, 199-214.

ESTERLE J.S., FERM J.C. & TIE Y.L. (1989). – A test for the analogy of tropical domed peat deposits to "dulling-up" sequence in coal beds; preliminary results. – *Org. Geochem.*, **14**, 333-342.

ETHERINGTON J.R. (1983). – Wetland ecology. – Studies in Biology No. 154, Arnold, London.

ETHRIDGE F.G., JACKSON T.J. & YOUNGBERG A.D. (1981). – Floodbasin sequence of a fine-grained meander belt subsystem : the coal-bearing lower Wasatch and upper Fort Union Formations, Southern Powder River Basin, Wyoming. *In :* ETHRIDGE F.G. and FLORES R.M. Eds., Recent and ancient nonmarine depositional environments : models for exploration. – *Soc. Econ. Paleontol. Mineral. Spec. Publ.* **31**, 190-209.

FLORES R.M. (1989). – Rocky Mountain Tertiary coal-basin models and their applicability to some world basins. – *Int. J. Coal Geol.*, **12**, 767-798.

FLORES R.M. (1981). – Coal deposition in fluvial paleoenvironments of the Paleocene Tongue River Member of the Fort Union Formation, Powder River area, Powder River Basin, Wyoming and Montana. *In :* ETHRIDGE F.G. and FLORES R.M. Ed., Recent and ancient nonmarine depositional environments : models for exploration. – *Soc. Econ. Paleontol. Mineral., Spec. Publ.* **31**, 169-190.

GORE A.J.P. Ed. (1983). – Mires : swamp, bog, fen and moor, (general studies); Ecosystems of the World, 4A. – Elsevier, Amsterdam.

GROSSE-BRAUCKMANN G. (1979). – Zur deutung einiger makrofossil vergesellschaftungen unter dem gesichtspunkt der torfbildung. *In :* WILLIAMS O. and TÜXEN R. Ed.: Werden und Vergehen von Pflanzengesellschaften. – Ber. Int. Symp. Int. Ver. Vegetationskunde, J. Cramer, Vaduz, 111-132.

GUERRA-SOMMER M., MARQUES-TOIGO M. & CORREA DA SILVA Z.C. (1990). – Original biomass and coal deposition in southern Brazil (Lower Permian, Parana Basin). – *Bull. Soc. géol. Fr.*, **162**, 2, 91-101.

HACQUEBARD P.A., BIRMINGHAM T.F. & DONALDSON J.R. (1967). – Petrography of Canadian coals in relation to environment of deposition; energy, mines and resources. – Symposium on Science and Technology of Coal, Ottawa, 84-97.

HACQUEBARD P.A. & DONALDSON J.R. (1964). – Stratigraphy and palynology of the Upper Carboniferous coal measures in the Cumberland Basin of Nova Scotia, Canada. – Compte Rendu, Cinquième Congrès International de Stratigraphie et de Géologie du Carbonifère, Paris, vol. 3, 1157-1169.

HACQUEBARD P.A. & DONALDSON J.R. (1969). – Carboniferous coal deposition associated with floodplain and limnic environments in Nova Scotia. – *Geol. Soc. Amer. Spec. Paper*, **114**, 143-191.

HACQUEBARD P.A. & DONALSON J.R. (1970). – Coal metamorphism and hydrocarbon potential in the Upper Paleozoic of the Atlantic Provinces, Canada. – *Can. J. Earth Sci.*, **7**, 1139-1163.

HARVEY R.D. & DILLON J.W. (1985). – Maceral distribution in Illinois coals and their paleoenvironmental implications. – *Int. J. Coal Geol.*, **5**, 141-165.

HEINSELMAN M.L. (1963). – Forest sites, bog processes, and peatland types in the glacial Lake Agassiz region, Minnesota. – *Ecol. Monog.* **33**, 327-374.

ICCP Handbook (1971). –

KEPPIE J.D. (1982). – The Minas geofracture. *In :* JULIAN P. St. and BELAND J. Eds., Major structural zones and fault of the northern Appalachians. – *Geol. Assoc. Canada, Spec. Paper* **24**, 263-280.

KOSTERS E.C., CHMURA G.L. & BAILEY A. (1987). – Sedimentary and botanical factors influencing peat accumulation in the Mississippi Delta. – *J. Geol. Soc.* (London), **144**, 423-434.

KULCZYNSKI S. (1949). – Peat bogs of Polesie. – *Mem. Acad. Sci. Cracovie* B., 1-356.

LI SITIAN, LI BAOFANG, YANG SHIGONG, HUANG JIAFU & LI ZHEN (1984). – Sedimentation and tectonic evolution of late Mesozoic faulted coal basins in north-eastern China. *In :* RAHMANI R.A. and FLORES R.M. Eds., Sedimentology of coal and coal-bearing

sequences. – *Spec. Public. Internat. Assoc. Sedimentol.*, **7**, 387-406.

LIPPOLT H.J. & HESS J.C. (1985). – $^{40}Ar/^{39}Ar$ dating of sanidines from Upper Carboniferous tonsteins. – Compte rendu, Dixième Congrès International de Stratigraphie et de Géologie du Carbonifère, Madrid, 1983, vol. 4, 176-181.

LITTKE R. (1987). – Petrology and genesis of Upper Carboniferous seams from the Ruhr region, West Germany. – *Int. J. Coal Geol.*, **7**, 147-185.

MASTALERZ M. & SMYTH M. (1988). – Petrography and depositional conditions of the 64/65 coal seam in the Intrasudetic Basin, SW Poland. – *Int. J. Coal Geol.*, **10**, 309-366.

MCCABE P.J. (1984). – Depositional environments of coal and coal-bearing strata. *In* : RAHMANI R.A. and FLORES R.M. Eds., Sedimentology of coal and coal-bearing strata. – *Spec. pub.*, International Association of Sedimentologists, **7**, 13-42.

MOORE P.D. (1987). – Ecological and hydrological aspects of peat formation. *In* : SCOTT A.C. Ed., Coal and coal-bearing strata : recent advances. – *Geol. Soc. London Spec. Publ.*, **32**, 7-15.

MOORE P.D. (1989). – The ecology of peat-forming processes : a review. – *Int. J. Coal Geol.* **12**, 89-103.

MOORE P.D. & BELLAMY D. (1974). – Peatlands. – Elek Science, London, 221 p.

MUKHOPADHYAY P.K. (1986). – Petrography of selected Wilcox and Jackson Group lignites from the Tertiary of Texas. *In* : FINKELMAN R.B. and CASSAGRANDE D.J. Eds., Geology of Gulf Coast lignites. – Environmental and coal associates, 126-145.

MUKHOPADHYAY P.K. (1989). – Organic petrography and organic geochemistry of Tertiary Coals from Texas in relation to depositional environment and hydrocarbon generation. – Report of Investigations, 188, Bureau of Economic Geology, Austin, Texas, 118 p.

MUKHOPADHYAY P.K. (1991). – Maturation of organic matter as revealed by microscopic methods : applications and limitations of vitrinite reflectance, continuous spectral and pulsed laser fluorescence spectroscopy. *In* : CHINGARIAN G.V. and WOLF K.H. Eds., Diagenesis. – Elsevier, Amsterdam, vol. 3, chapt. 9.

NANCE R.D. (1987). – Dextral transpression and late Carboniferous sedimentation in the Fundy coastal zone of southern New Brunswick. *In* : BEAUMONT C. and TANKARD A.J. Eds., Sedimentary basins and basin-forming mechanisms. – *Can. Soc. Petrol. Geol., Mem.* **12**, 363-377.

OBERNYER S. (1978). – Basin-margin depositional environments of the Wasatch Formation in the Buffalo-lake de Smet area, Johnson County, Wyoming. *In* : HODGSON H.W. Ed., 1977 Proceedings of the 2nd Symposium on the Geology of Rocky Mountain Coal. – *Colorado Geol. Surv. Res. Ser.* **4**, 49-65.

PENFOUND W.T. (1952). – Southern swamp and marshes. – *The Botanical Review*, **18**, 413-446.

PHILLIPS T.L., PEPPERS R.A. & DIMICHELE W.A. (1985). – Stratigraphic and interregional changes in Pennsylvanian coal-swamp vegetation : environmental influences. – *Int. J. Coal Geol.*, **5**, 43-109.

POLAK B. (1933). – Ueber torf und moor Niederlandisch Indien. – *Verh. K. Akad. Wet.*, Amsterdam, **30.**

POLAK B. (1975). – Character and occurrences of peat deposits in the Malaysian tropics. *In* : BARTSTRA G.J. and CASPARIE W.A. Eds., Modern Quaternary research in Southeast Asia. – Balkema, Rotterdam, 71-81.

SCOTESE C.R., BAMBACH R.K., BARTON C., VAN DER VOO R. & ZIEGLER A.M. (1979). – Paleozoic base maps. – *J. Geol.*, **87**, 217-277.

SCOTT A.C. (1989). – Observation on the nature and origin of fusain. – *Int. Coal Geol.*, **12**, 443-475.

SMITH A.H.V. (1962). – The paleoecology of Carboniferous peats based on the miospores and petrography of bituminous coals. – *Proc. Yorkshire Geol. Soc.*, **33**, 423-474.

STACH E., MACKOWSKY M.-Th., TEIMÜLLER M., TAYLOR G.H., CHANDRA D. & TEICHMÜLLER R. (1982). – Coal petrology (third edition). – Gebrüder Borntraeger, Berlin, Stuttgart, 535 p.

STANTON R.W., MINKIN J.A. & MOORE T.A. (1987). – Petrographic properties of coal and rock samples. *In* : ROEHLER H.W. and MARTIN P.L. Eds., Geological investigations of the Vermillion Creek Coal Bed in the Eocene Niland Tongue of the Wasatch Formation, Sweetwater County, Wyoming. – *U.S. Geol. Surv. Prof. Paper*, **1314 A-L**, 105-120.

STOUT S.A. & SPACKMAN W. (1987). – A microscopic investigation of woody tissues in peats : some processes active in the peatification of ligno-cellulosic cell walls. – *Int. J. Coal Geol.*, **8**, 55-68.

TALLIS J.M. (1983). – Changes in wetland communities. *In* : GORE A.J.P., Mires : swamp, bog, fen and moor (general studies); ecosystems of the World 4A. – Elsevier, Amsterdam, 311-348.

TANSLEY A.G. (1911). – Types of British vegetation. – Cambridge University Press.

TANSLEY A.G. (1939). – The Bristish Islands and their vegetation. – Cambridge University Press.

TEICHMÜLLER M. & TEICHMÜLLER R. (1958). – Inkohlungsuntersuchungen und ihre Nutzanwendung. – *Geol. Mijnb.*, 2, N.S., **20**, 41-66.

TEICHMÜLLER M. (1962). – Die Genese der Kohle. – Compte Rendu Quatrième Congrès International de Sratigraphie et de Géologie du Carbonifère, Heerlen, 1958; vol. 3, 699-722.

TEICHMÜLLER M. (1982). – Origin of the petrographic constituents of coal. *In* : STACH E., MACKOWSKY M.-Th., TEICHMÜLLER M., TAYLOR G.H., CHANDRA D., TEICHMÜLLER R. Eds., Stach's textbook of coal petrology. – Gebrüder Borntraeger, Berlin-Stuttgart, third edition, 219-294.

TEICHMÜLLER M. (1989). – The genesis of coal from the viewpoint of coal petrology. – *Int. J. Coal Geol.*, **12**, 1-87.

TIMOFEEV P.P. & BOGOLIUBOVA L.I. (1964). – Main factors in the formation of genetic types of humic coals and the specific features of their distribution in different coal-bearing formations of the USSR. – Compte Rendu Cinquième Congrès International de Stratigraphie et de Géologie du Carbonifère, Paris, 1964.

WARWICK P.D. & FLORES R.M. (1987). – Evolution of fluvial styles in the Eocene Wasatch Formation; Powder River Basin, Wyoming. *In* : ETHRIDGE F.G., FLORES R.M. and HARVEY M.D. Ed., Recent developments in fluvial sedimentology. – *Soc. Econ. Paleontol. Mineral. Spec. Publ.* **39**, 303-310.

WARWICK P.D. & STANTON R.W. (1988). – Depositional models for two Tertiary coal-bearing sequences in the Powder River Basin, Wyoming, USA. – *J. Geol. Soc.*, London, **145**, 613-620.

WEBER C.A. (1908). – Aufbau und vegetation des moore Nord-Deutschlands. – *Engler's Bot. Jahrb.*, **40** (Suppl.), 19-34.